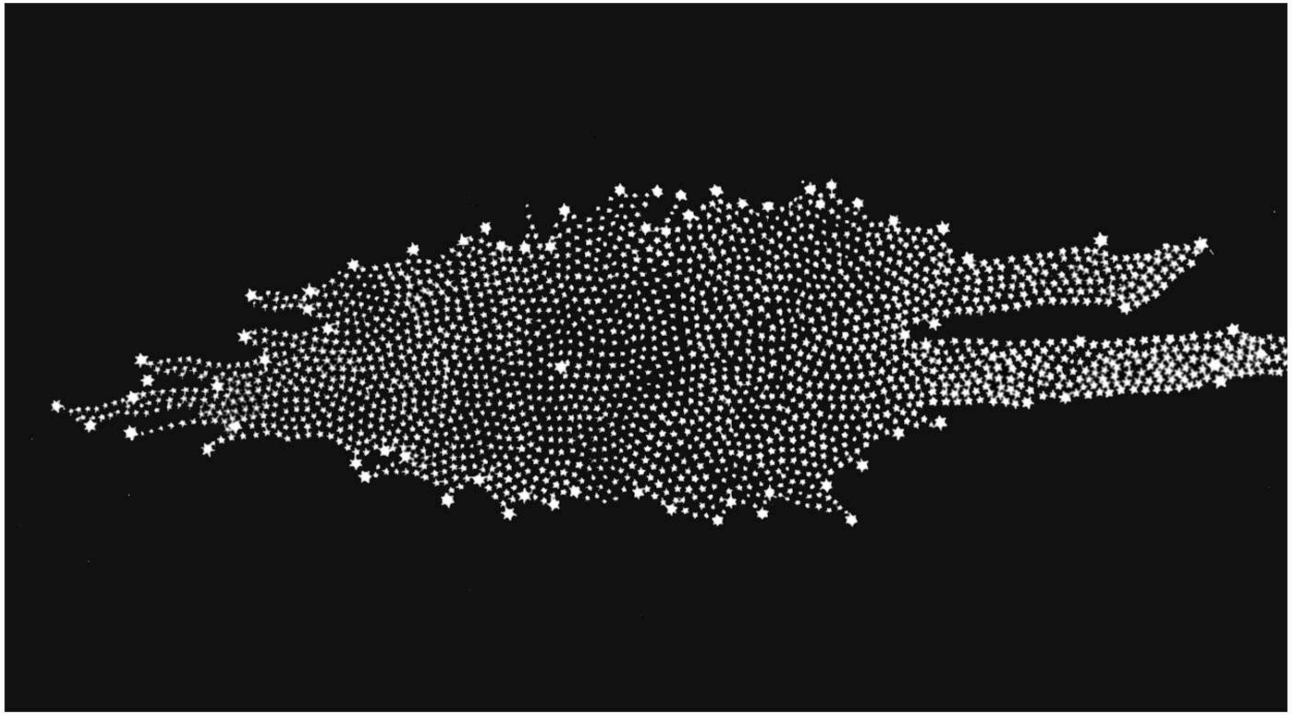
Numbers to Keep in Mind

- 21 cm = wavelength of H I spin flip
- 1/233 = Gravitational Constant (units of pc, km/s, and $M_\odot$)
- ~ 8 kpc = distance to the Galactic center
- ~ 220 km/s = orbital velocity of the Sun about the Galaxy
- ~ 19.5 km/s = motion of Sun with respect to nearby stars
- ~ 10^{12} $M_\odot$ = mass of Milky Way
- ~ 30 kpc = size of Milky Way



The Milky Way

Milky Way: drawing by William Herschel (1783) vs. photograph.

- Most stars located in a plane
- Obvious dust lanes

Forms of the Interstellar Medium

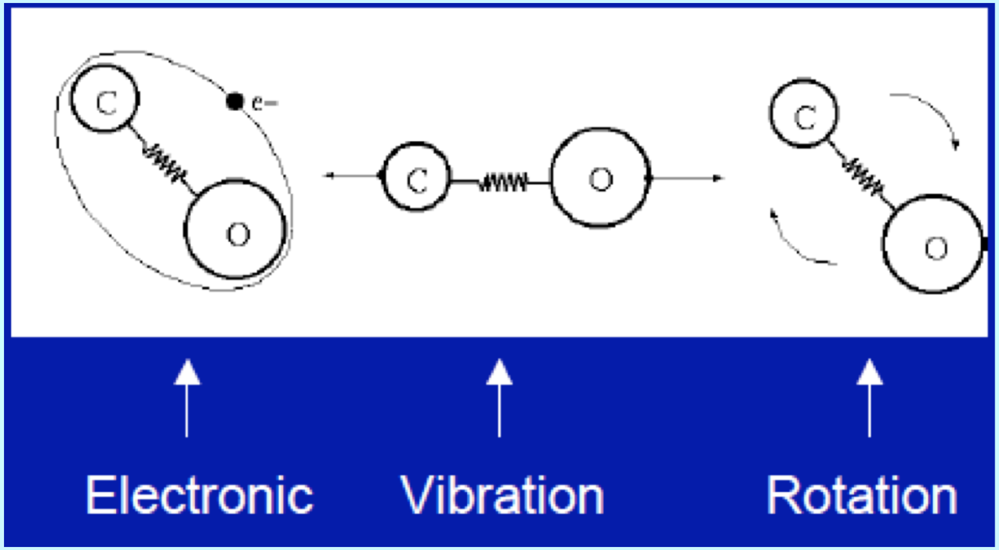
Roughly half the baryonic mass of the Milky Way is in the form of interstellar gas and dust. This material is constantly being recycled into and out of stars, and being augmented by infall from outside the galaxy. The ISM takes on several forms:

Type	Volume	Scale Height	Density (cm^{-3})	Temperature (° K)	Name
Cold, dense	< 1%	~ 80 pc	$> 10^2$	< 20	molecular
Cold, neutral	~ 5%	~ 100 pc	~ 20	$\sim 10^2$	H I
Warm, neutral	~ 50%	~ 1 kpc	~ 1	$\sim 10^4$	WIM
Warm	< 1%	~ 80 pc	~ 1	$\sim 10^4$	H II
Hot	> 50%	---	$\sim 10^{-3}$	$\sim 10^6$	X-ray

Molecular Gas

When the ISM density becomes greater than ~ 10^2 cm^{-3}, collisions between atoms (and with dust) become frequent enough to form (and maintain) molecules. These molecules emit via electronic, vibrational, and rotational transitions.

Molecular clouds contain a large variety of molecules. Collisions with other atoms and dust grains build up the molecules; UV radiation destroys them. Examples are:



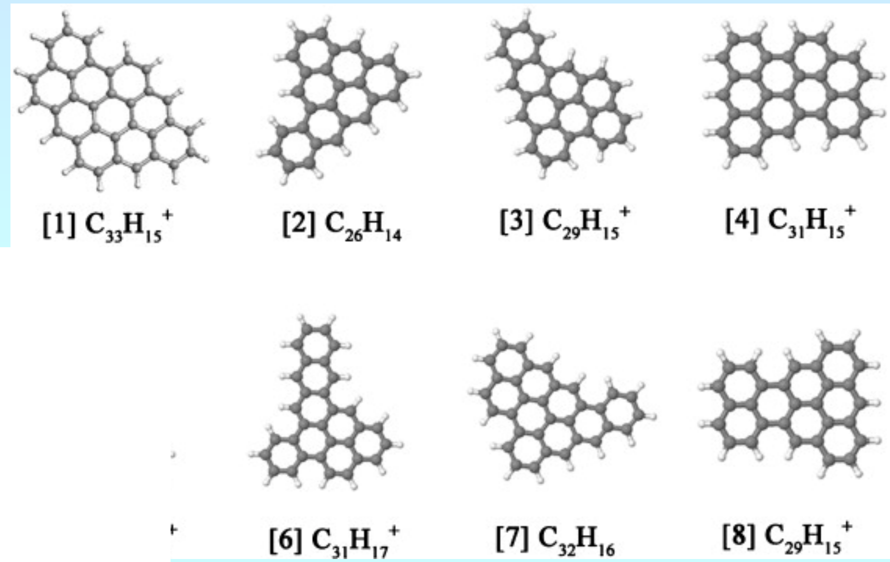
$$O + H \rightarrow OH + C \rightarrow COH + 3H \rightarrow CH_3OH$$

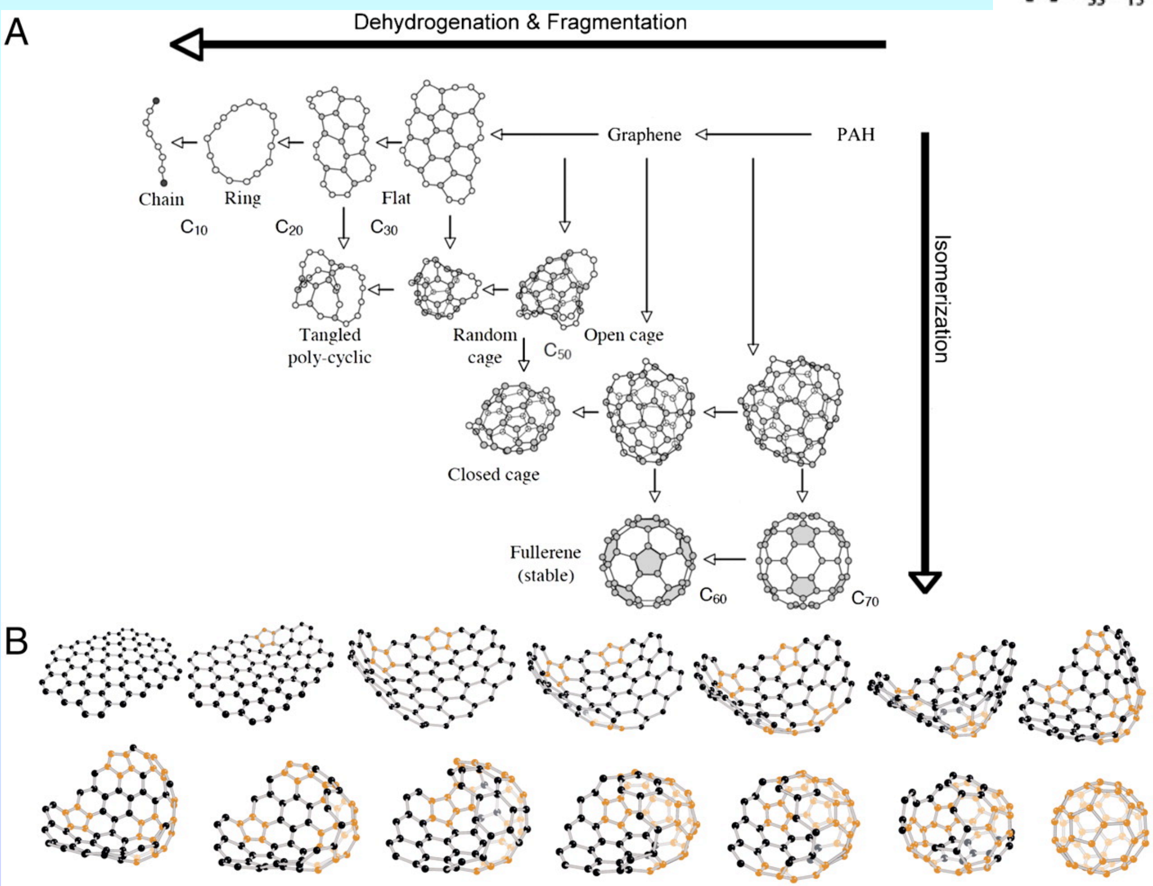
$$CH + H \rightarrow CH_2 + O \rightarrow H_2CO$$

$$C + H \rightarrow CH + COH \rightarrow C_2HOH + 4H \rightarrow CH_3CH_2OH$$

PAHs

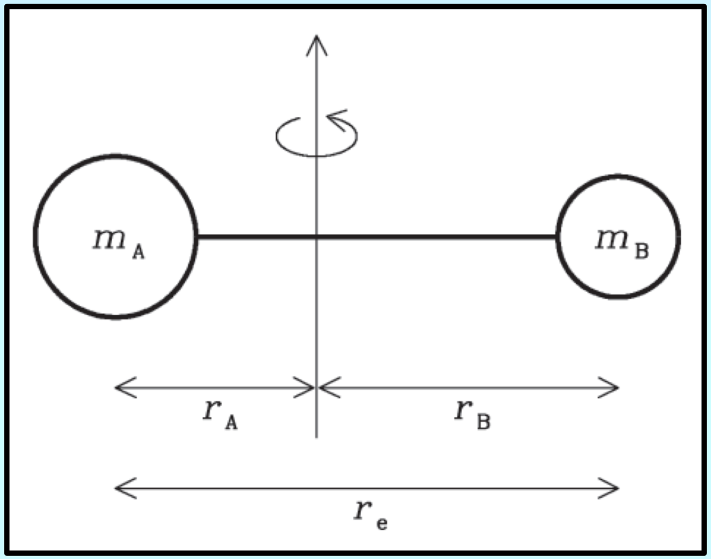
Molecules in the ISM can become quite complex. The emission features of many polycyclic aromatic hydrocarbons (PAHs) have been detected.





Molecular Gas

Molecules efficiently radiate via rotational transitions. As in atoms, permitted transitions must have $J = \pm\, 1$, and the (quantized) angular momentum of a molecule is



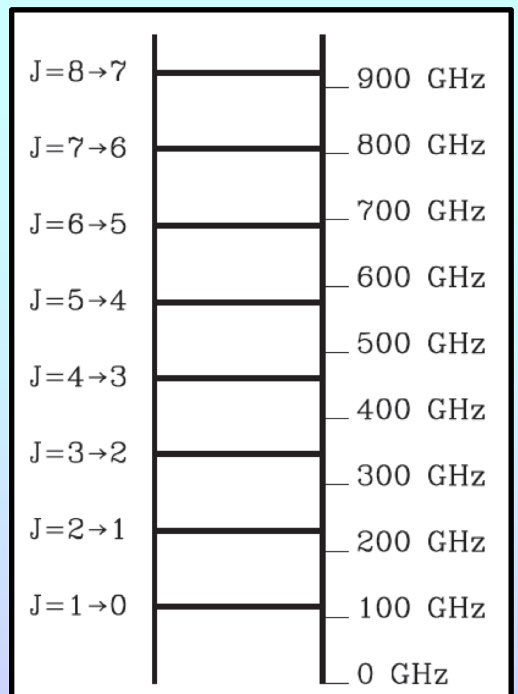
$$L = I\omega = \left(m_A r_A^2 + m_B r_B^2\right)\omega$$

$$= \left(\frac{m_A m_B}{m_A + m_B}\right) r_e^2 \omega = m\, r_e^2 \omega$$

$$E_{rot} = \frac{I\omega^2}{2} = \frac{L^2}{2I} = \frac{J\left(J+1\right)\hbar}{2I}$$

$$\Delta E_{rot} = \left[J\left(J+1\right) - \left(J-1\right)J\right]\frac{\hbar}{2I} = \frac{\hbar}{I} J$$

$$\nu = \frac{\Delta E_{rot}}{h} = \frac{\hbar}{2\pi I} J \quad \text{for} \quad J = 1, 2, 3 \ldots$$



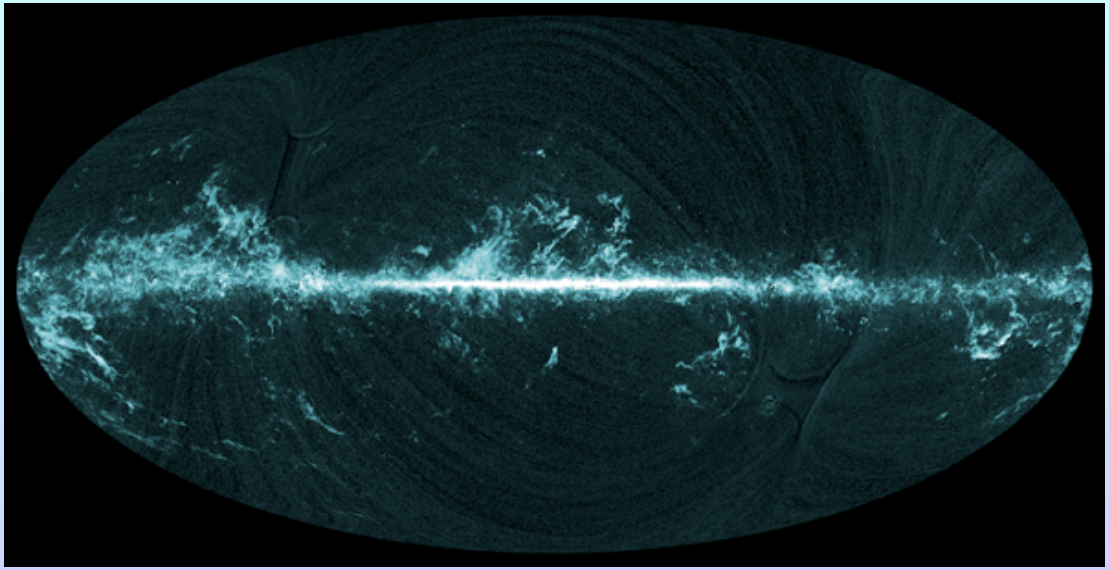
Thus, rotational transitions come in a series of rungs.

Molecular Gas

The frequency of a rotation transition with $\Delta J = 1$ is then given by

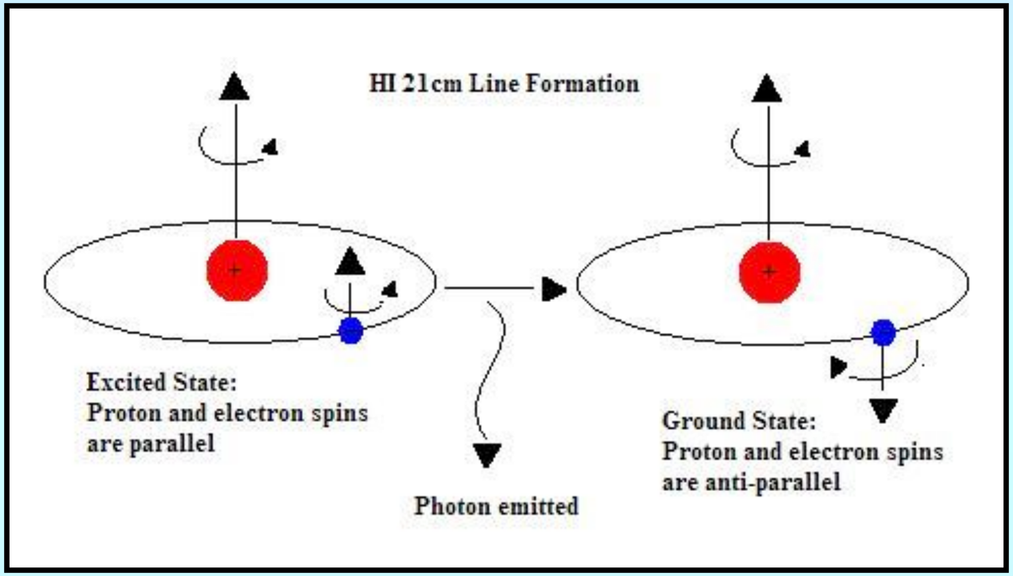
$$\nu = \frac{\hbar}{2\pi I} J = \frac{h}{4\pi^2 m r_e^2} J \propto m^{-1} r_e^{-2}$$

where m is reduced mass. Since $\nu \propto m^{-1}$, H_2 transitions occur at relatively high energies, $T \sim E_{\min} / k \sim 500°$ K. But this is much hotter than the interior of a molecular cloud! H_2 is thus not observable. A much more tractable molecule is CO, for which J = 1 → 0 transition is at 115.27 GHz. Most mappings of molecular clouds occurs with CO.



Atomic Hydrogen

Atomic hydrogen in the Milky Way can best be detected via the hyperfine transition at 21 cm.



$\Delta E = 5.87 \times 10^{-6}$ eV

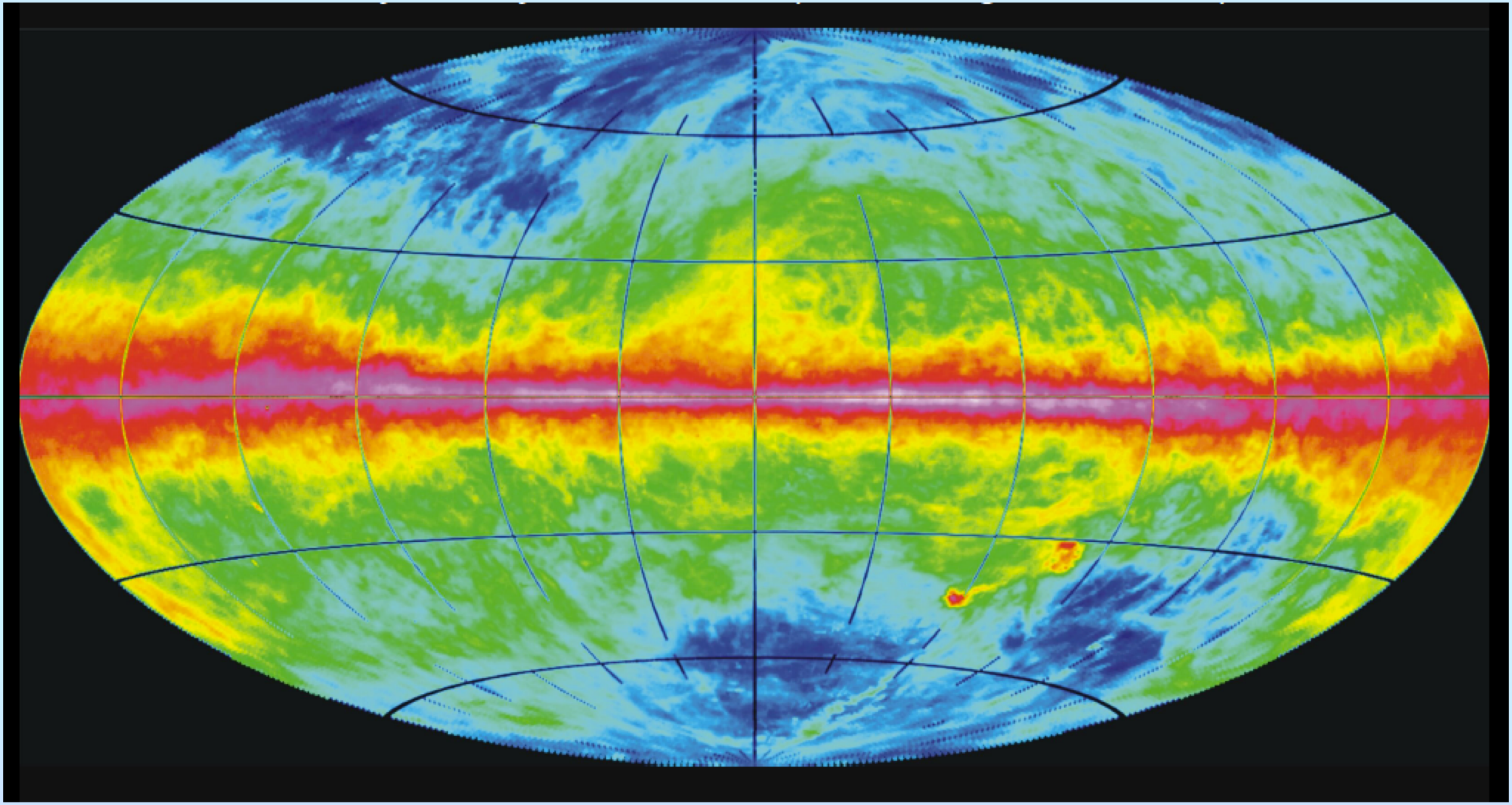
$\lambda = 21$ cm

$\nu = 1420.4$ MHz

$A = 2.8843 \times 10^{-15}$ sec^{-1}

Atomic Hydrogen

Because 21 cm emission is relatively easy to detect, and is not absorbed (by gas or dust) it is easy to map out its distribution in the Galaxy.

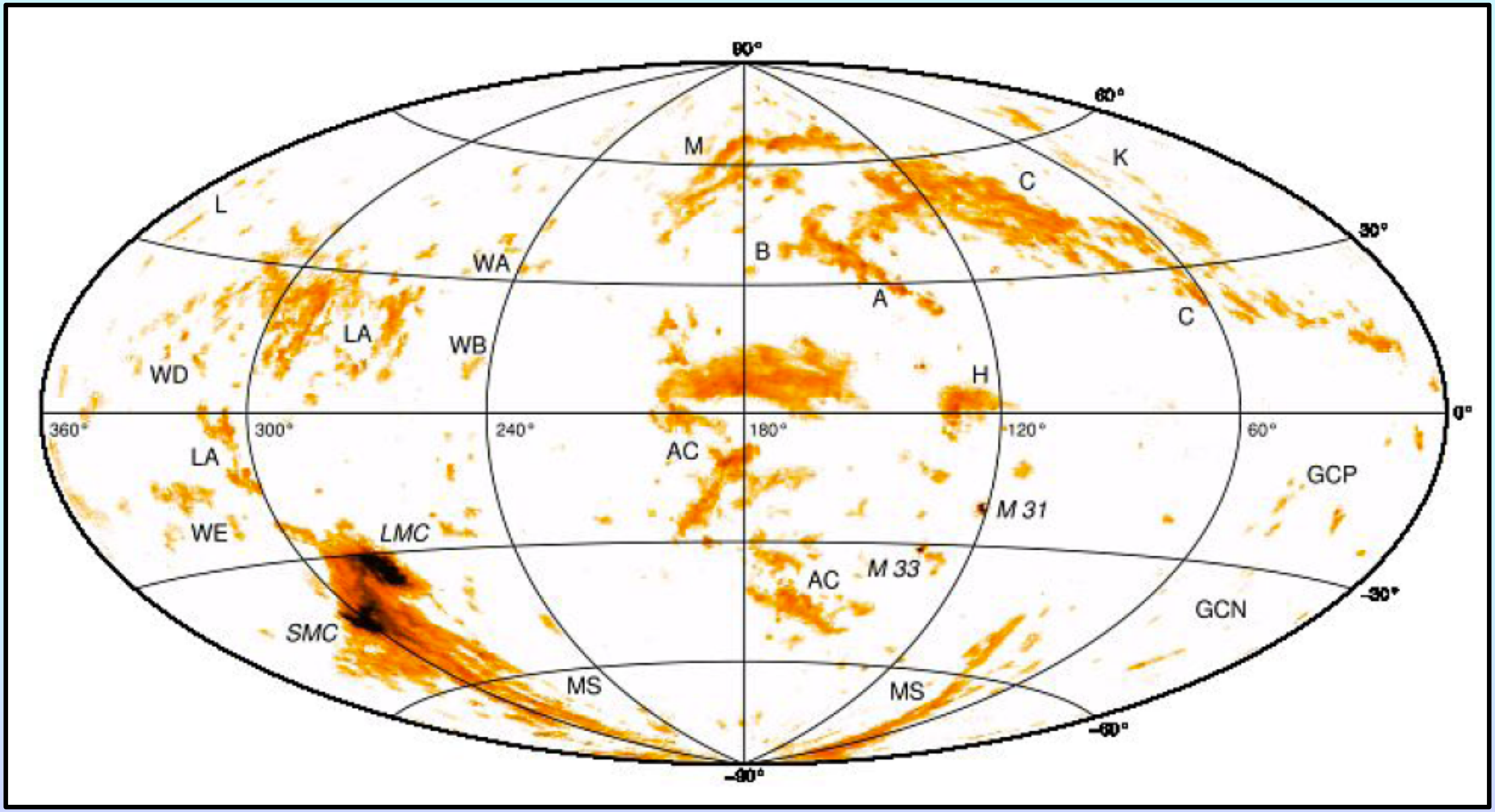


[Hartmann & Burton 1997, "Atlas of Neutral Hydrogen"]

[Burstein & Heiles 1982, AJ, 87, 1165]

H I Velocities

Most H I is rotating about the Galactic center. However, some H I clouds have velocities that differ from that expected by > 50 km/s. The question of where these “High Velocity Clouds” are is still open.



X-ray Gas

A large fraction of the gas associated with the Milky Way is in the form of X-ray emitting plasma. This gas can be heated by

- The energy from stellar winds: Protons and helium nuclei are coming off the Sun at a velocity of ~ 200 km/s. (This is the solar wind.) OB stars have winds of ~ 2000 km/s. So, if this gas thermalizes, then

$$\frac{1}{2} m_H v^2 \sim \frac{3}{2} kT \quad \Rightarrow \quad T \sim 0.4 \left(\frac{v}{100 \text{ km/s}} \right)^2 \text{ million degrees}$$

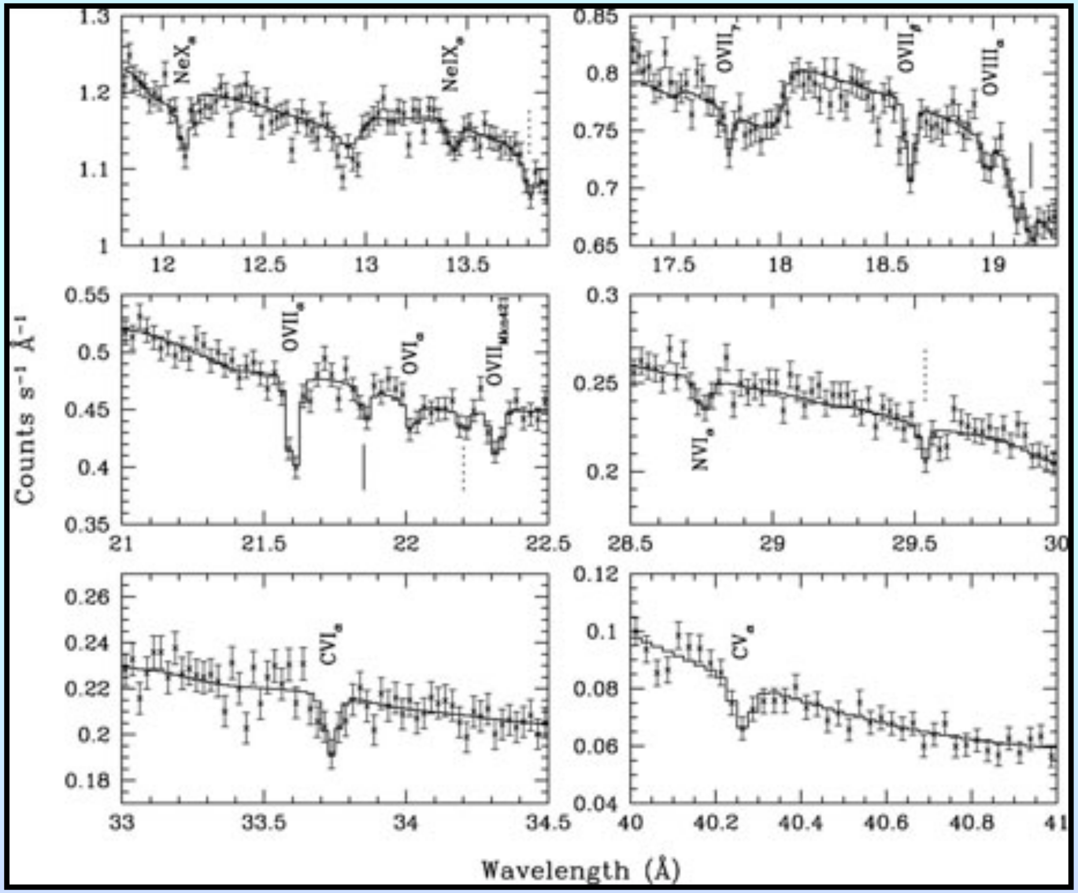
- Supernovae: the velocity of supernova ejecta is ~ 10,000 km/s. If this gas thermalizes, even with 1% efficiency, then $T > 10^7$ K.

- Infall: intergalactic gas falling into the Milky Way has energy equivalent to

$$\frac{G M_{\text{gal}} m_p}{R} \sim \frac{3}{2} kT \quad \Rightarrow \quad T \sim 20 \text{ million degrees}$$

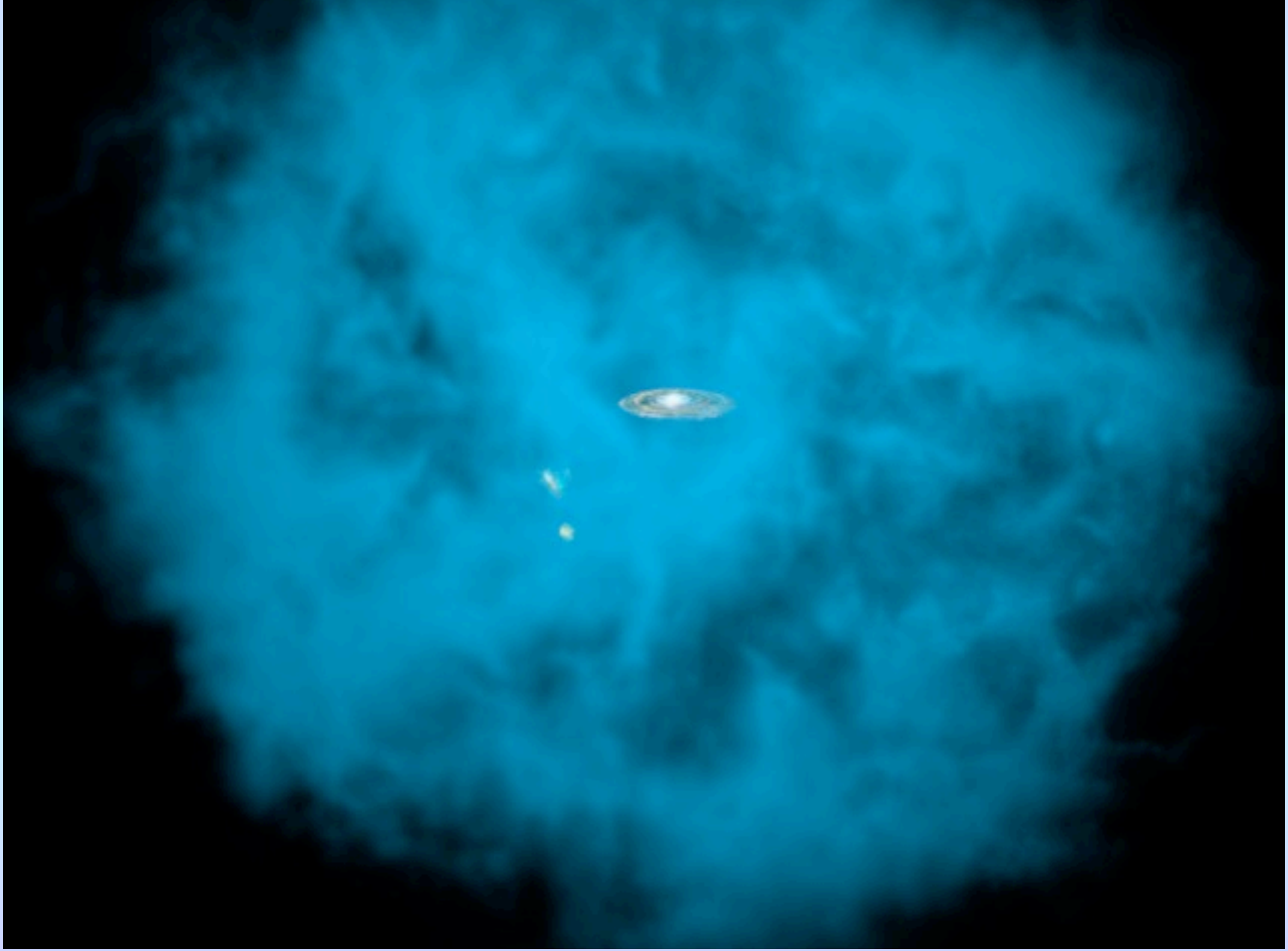
X-ray Gas

Because of its low density, the Galaxy's X-ray gas is extremely difficult to detect. Its existence is inferred from z = 0 absorption lines of highly ionized species in the spectra of distant quasars, etc.



This soft X-ray gas is sometimes called the WHIM, for "Warm Hot Interstellar Medium". There also may be hotter "coronal" gas in the halo of the Milky Way.

Possible Distribution of the X-ray gas

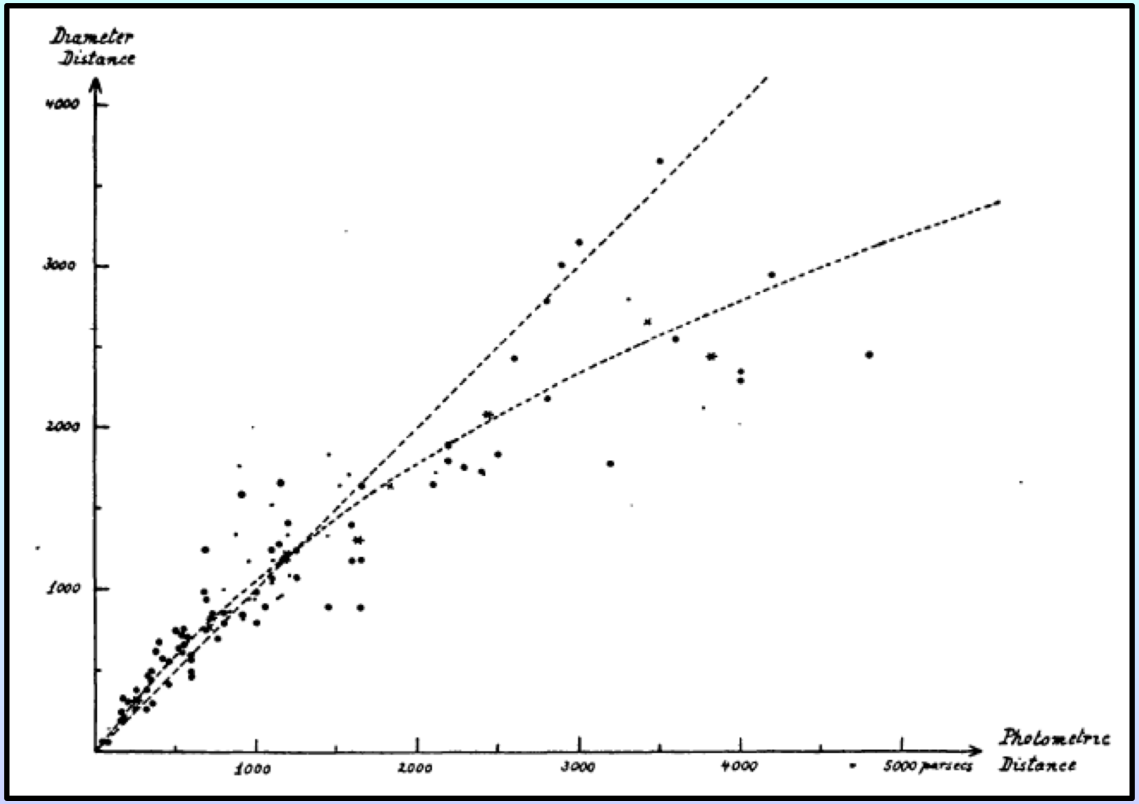


Dust

Dust is made in the atmospheres of red giant stars (and novae and supernovae). At this time, much of Fe and Si, ~ ½ of C, and maybe ~20% of O is locked up in dust grains.

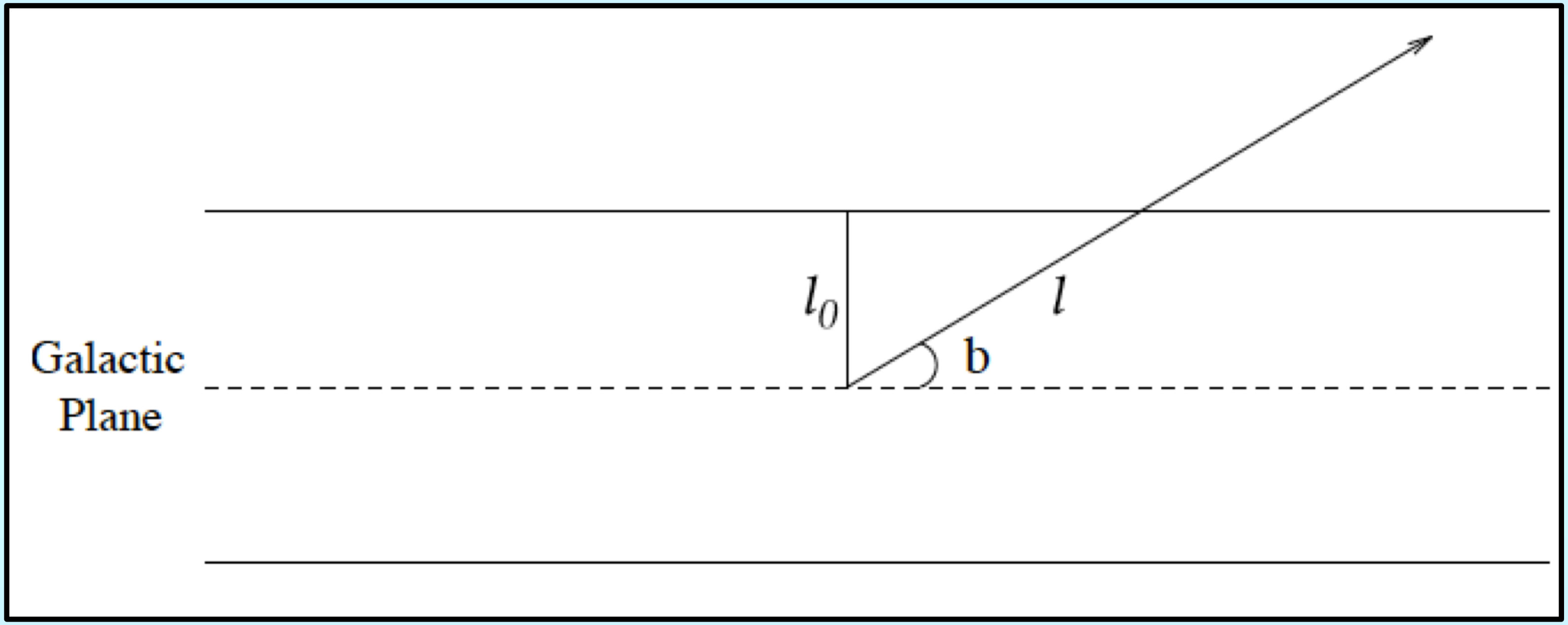
• There are many different types of dust; a (very rough) division is "silicates" and "graphites". The emission and absorption features of each are slightly different.

• Dust is not restricted to the "dark lanes" in the Galaxy; there is also a diffuse component, first detected by Trumpler (1930) from the studies of star clusters. It thus effects *all* measurements of luminosity.



Dust Distribution

The distribution of dust in the Galaxy is not uniform. A zero-th order approximation is that the amount of extinction depends on the csc of Galactic latitude: if the dust scale-height is l_0 and κ is the opacity, then



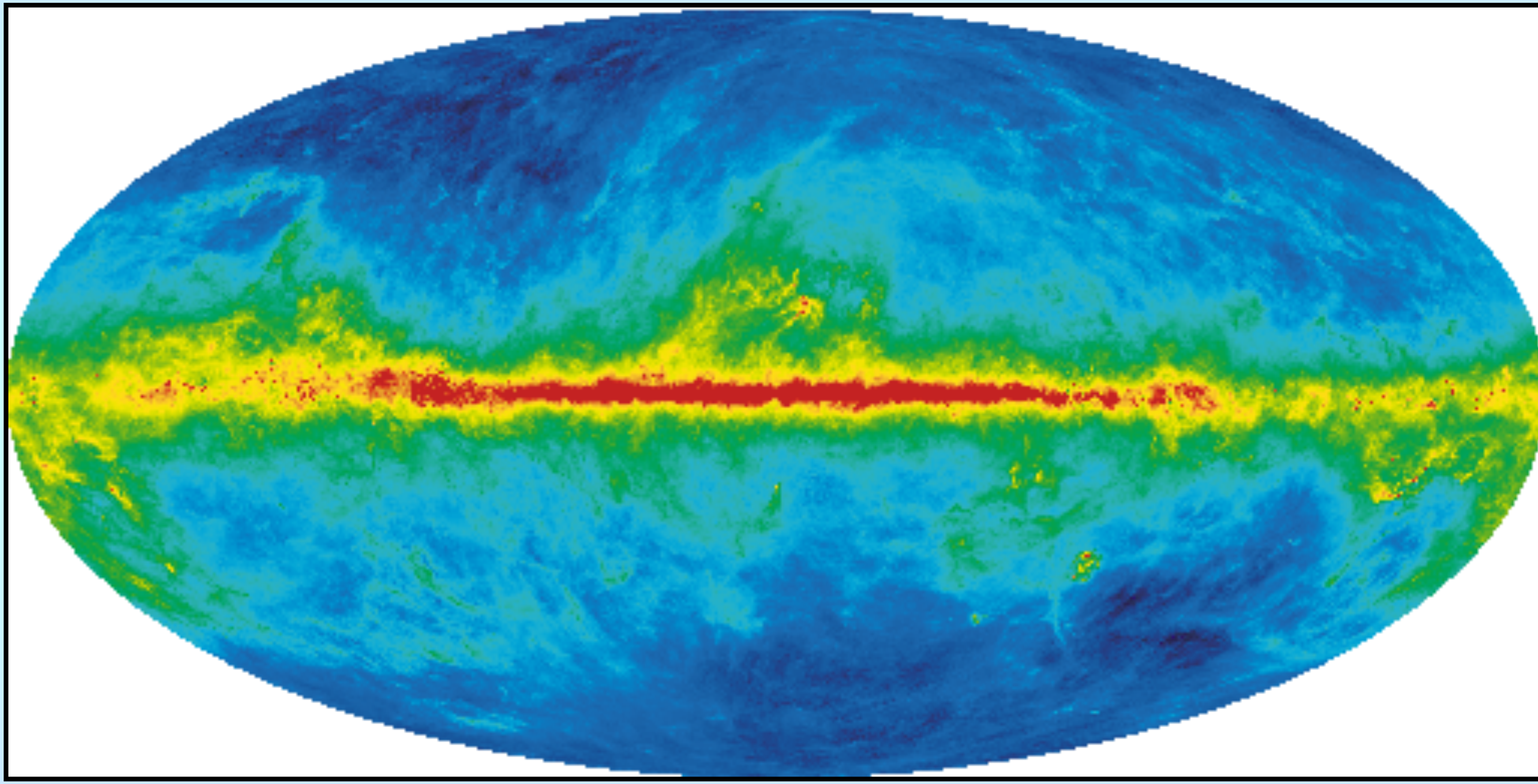
$$I = I_0 e^{-\kappa l} = I_0 e^{-\kappa l_0 \csc b} \quad \Rightarrow$$

$$-2.5 \log I = -2.5 \log I_0 + 2.5(\log e) \kappa l_0 \csc b \quad \Rightarrow$$

$$\Delta m = K \csc b \quad \text{where} \quad K = 2.5 \kappa l_0 (\log e) = 1.086 \kappa l_0$$

Dust Distribution

The best estimates of the distribution of dust today are from far-IR maps of dust emissivity.



[Schlegel et al. 1998, ApJ, 500, 525]
[Schlafly et al. 2011, ApJ, 737, 103]

Also the Planck satellite has its own dust map

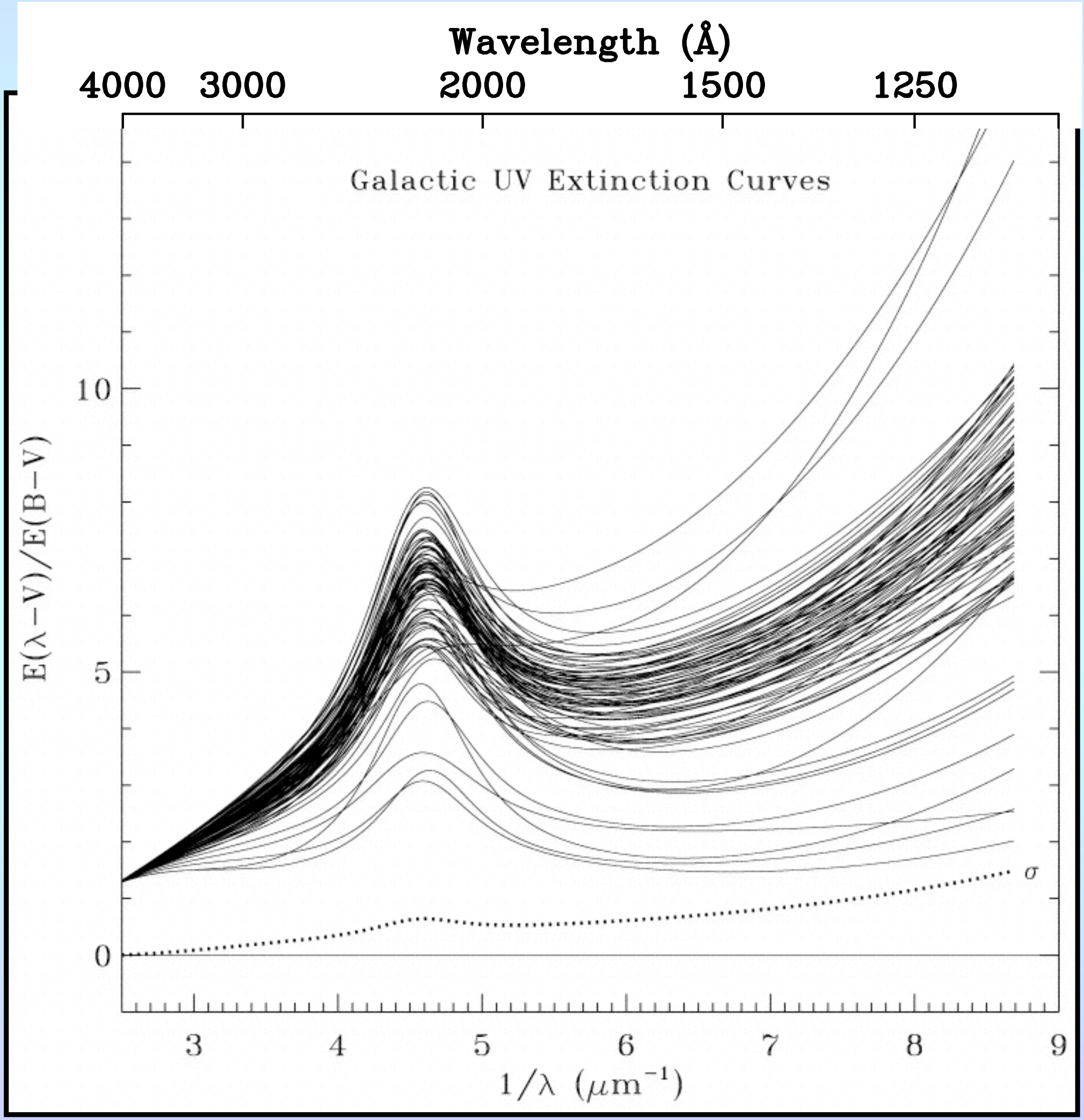
Dust

• Cold dust typically has a temperature between ~ 20° and 100° K; this puts its equilibrium blackbody peak in the far-IR (i.e., in the 24 μm, 60 μm, and 100 μm bands of satellite observatories). Dust can also emit at non-equilibrium temperatures (~ 1 to ~25 μm) when struck by UV photons. Finally, there are some broad, poorly-understood emission-features associated with some dust grains.

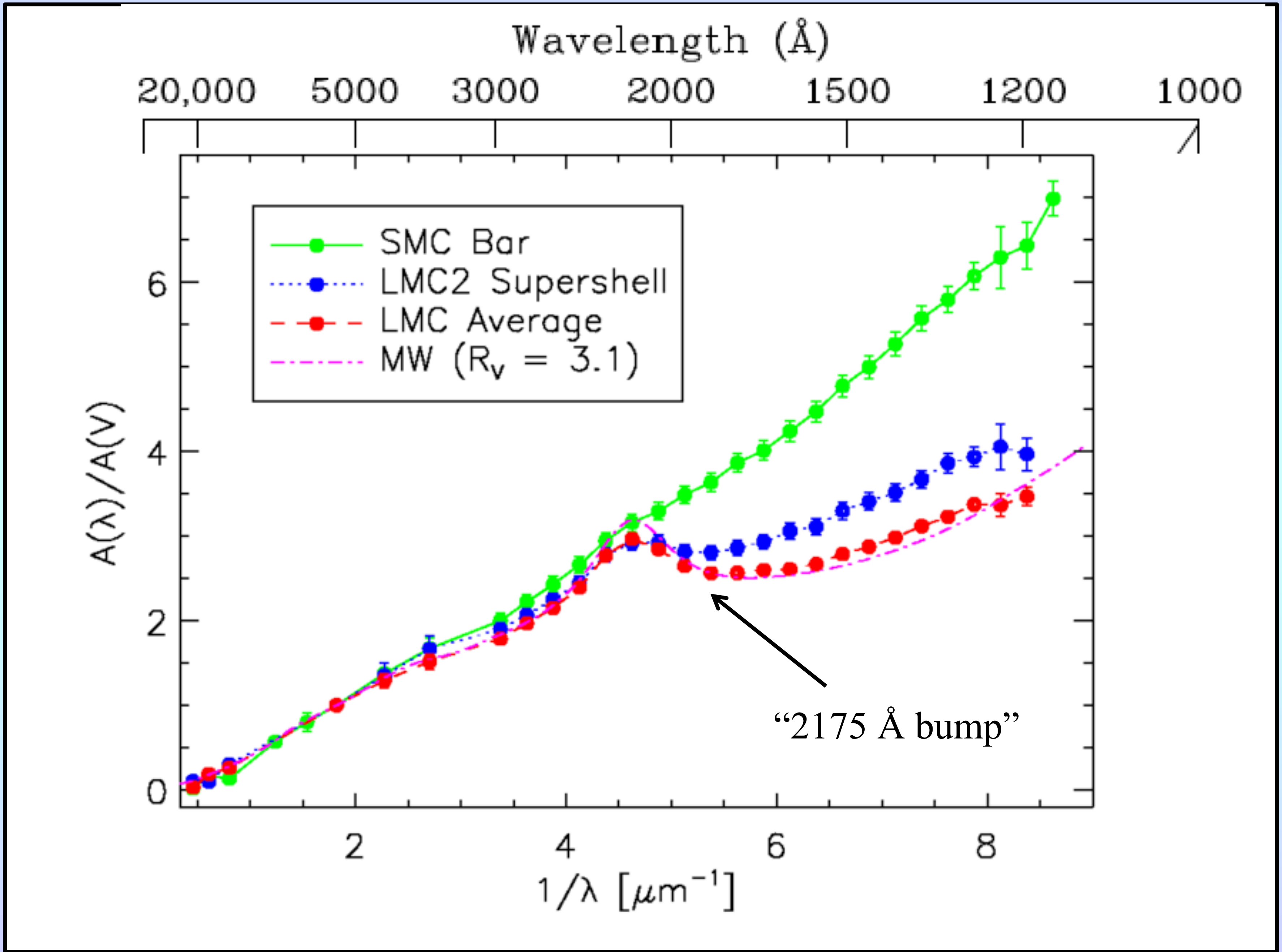
• The effect of dust extinction varies with wavelength, and is usually represented (in magnitudes) by R_λ. The amount of dust between the observer and a source is usually parameterized by the difference in extinction between the B and V filter passbands, i.e., $E(B-V)$. The total extinction at any wavelength is therefore $A_\lambda = R_\lambda\, E(B-V)$. The ratio of total to differential extinction in the optical is $R_V \sim 3.1$, with variations of $\pm$ 0.1 or so possible due to different types of dust.

• In the optical, the amount of extinction goes roughly as $1/\lambda$. However, there are features in the ultraviolet, and not all Milky Way sightlines have the same extinction curve.

Wavelength Dependence of Different Sightlines



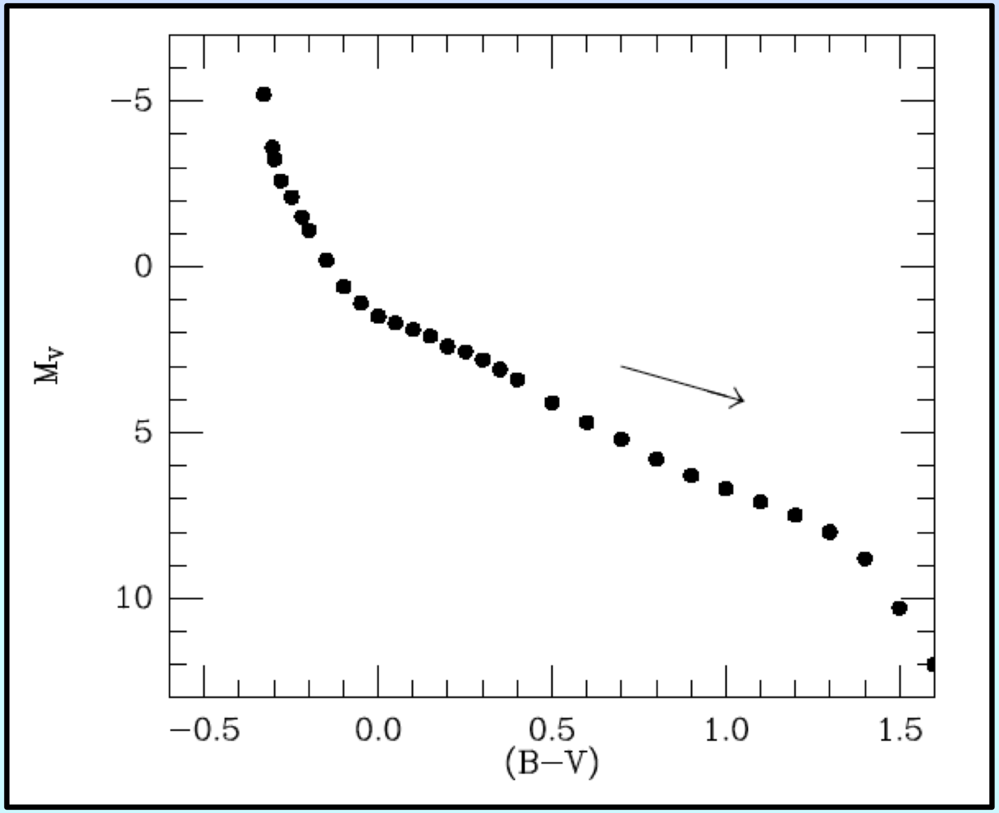
Extinction Laws



Extinction Laws

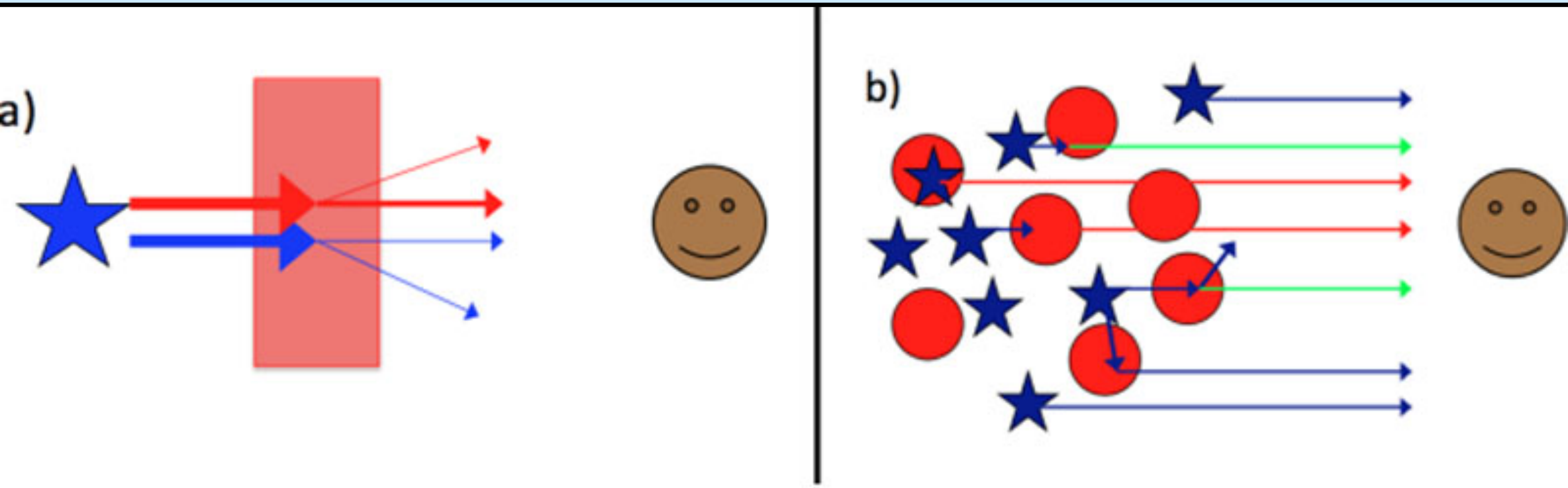
The ratio of total to differential extinction in the optical is not quite parallel to the main sequence. "Standard" values are $R_B = 4.1$, $R_V = 3.1$, $R_R = 2.3$, and $R_I = 1.5$.

Often used extinction curves are



[Savage & Mathis 1979, ARA&A, 17, 73]
[Cardelli et al. 1989, ApJ, 345, 245]
[Bouchet et al. 1985, A&A, 149, 330]
[Fitzpatrick 1999, Pub.A.S.P., 111, 63]
[Gordon et al. 2003, ApJ, 594, 279]

Side Note: Extinction versus Attenuation



These days, many astronomers seem to get confused between dust extinction (foreground dust acting as a screen) and attenuation of light from a system of stars (often a galaxy) caused by an intermixture of stars and dust. The most famous attenuation law is that by Calzetti (2001), PASP 113, 1149.   Don’t get them confused!

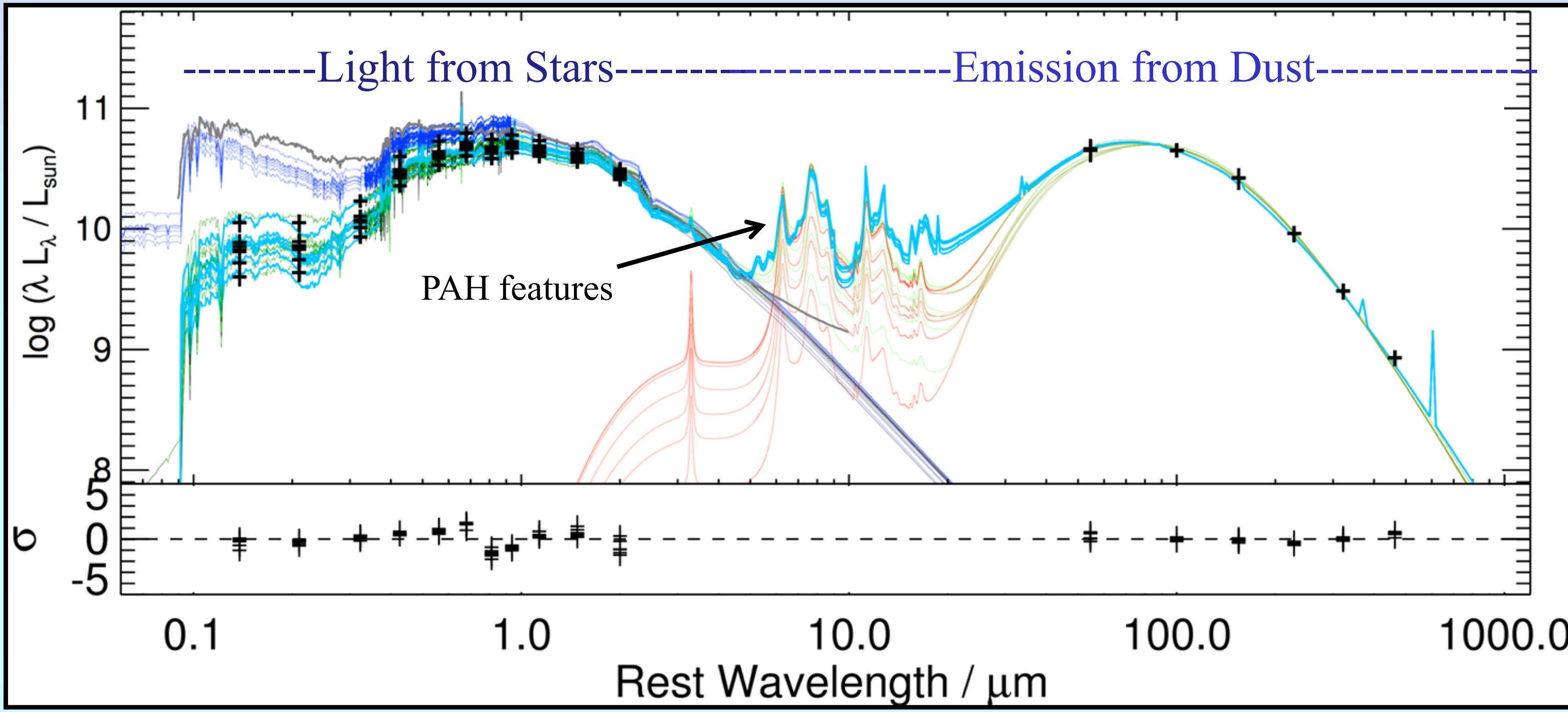
Dust

- By mass, the dust fraction of the Milky Way is insignificant: the gas-to-dust ratio in the Galaxy is ~ 100:1. In any sightline, the ratio of atomic hydrogen to dust extinction is

$$\frac{N(\mathrm{H\ I})}{E(B-V)} \sim 5 \times 10^{21} \text{ atoms-cm}^{-2}\text{-mag}^{-1}$$

- Despite its small mass, dust is very efficient at absorbing and re-radiating light. Between ⅓ and ½ of the starlight produced by the Milky Way is absorbed and re-radiated by dust in the far-IR.

Galaxy Spectral Energy Distributions: Stars + Dust



A large fraction of the energy of star-forming galaxies comes out in the mid- and far-IR. (Note the *y*-axis units: λL_λ has units of energy/sec).